

## Neutrino astrophysics and cosmology : recent developments

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**Abstract** In this talk, I have discussed some issues of recent interest and activity in the field of neutrino astrophysics and cosmology. The topics are (1) The origin of high peculiar velocities of pulsars, (2) Energization of the supernova shock wave, (3) Ultrahigh energy neutrino astronomy, (4) Possible implications of the recent measurements of low deuterium abundance.

**Keywords** Neutrino astrophysics, cosmology possible

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### 1. Introduction

It was known, since the birth of modern astrophysics in the early part of the 20th century, that neutrinos play an important role in various processes that occur within a stellar core and which are responsible for energy generation in a star. Gradually, the importance of neutrinos were understood in stars outside the main sequence. And, since the discovery of the microwave blackbody radiation, it was taken for granted that there is a similar cosmic background of neutrinos, although experimentally this background has not been detected so far. Various constraints from neutrino properties have been deduced from this belief, some of which are much better than the corresponding constraints from earth-based experiments. For example, one can cite the mass bound on stable neutrinos which are derived from the energy density of the universe as a whole. This sets an upper bound of order of a few tens of eV, whereas the direct measurement of the mass of  $\nu_\tau$  sets upper bounds in the range of a few tens of MeVs. If the neutrinos are unstable, then also there exists quite severe bounds on their lifetimes.

Unfortunately, in this talk I cannot review all of these aspects. Rather, I will have to assume that the audience is familiar with these concepts. The reason is that, fortunately, there has been a lot of progress in the field of neutrino astrophysics in the last year and a half, and quite a few of them are remarkable. I have to concentrate on these recent developments. I cannot guarantee that I will cover even all of the interesting recent developments. Let me say

I will cover what I know, with the restriction that I will leave out topics such as solar neutrinos and atmospheric neutrinos, for which many reviews exist.

## 2. Pulsar kicks and neutrinos

It has been known for some time [1, 2] that pulsars have large peculiar velocities, of the order of a few hundreds of kilometers per second. The average value, from a sample of about a hundred pulsars, is  $450 \pm 90 \text{ km s}^{-1}$ . The reason for such high velocities is not clearly understood.

Pulsars are rotating neutron stars which are believed to have a large surface magnetic fields. They are born from supernova explosions. It is not impossible that they get a kick from this explosion, provided the supernova collapse is asymmetric. Recently, however, Kusenko and Segrè [3] have suggested a very elegant mechanism in which, even though the matter density is spherically symmetric, the neutrino emission is not, and this provides a clue to the understanding of the pulsar kicks. The scenario involves some intricacies of neutrino physics, and provides some insight into neutrino masses. In this section, we will try to understand their idea.

Typical pulsars have masses between  $1.0M_{\odot}$  and  $1.5 M_{\odot}$ , *i.e.*, about  $2 \times 10^{33} \text{ g}$ . The momentum associated with the proper motion of a pulsar would therefore be of order  $10^{41} \text{ g cm/s}$ . On the other hand, the energy carried off by neutrinos in a supernova explosion is about  $3 \times 10^{53} \text{ erg}$ , which corresponds to a sum of the magnitudes of neutrino momenta of  $10^{43} \text{ g cm/s}$ . Thus, an asymmetry of the order of 1% in the distribution of the outgoing neutrinos would explain the kick of the pulsars.

How could this asymmetry be generated? The key issue is the propagation of neutrinos in a magnetic field. It is, of course, trivially true that if neutrinos have some magnetic moment, their motion will be affected by an external magnetic field. The more non-trivial result, shown earlier by D'Olivo *et al* [4], is that the motion of neutrinos are affected in the presence of a background magnetic field even if they do not have any intrinsic magnetic moment, or indeed any property that are not part of the standard model of particle interactions. In other words, even if the neutrinos are massless (and consequently have no intrinsic magnetic moment), they acquire an effective magnetic moment [5] due to their weak interaction with particles in the medium. As a result, the dispersion relation of massless neutrinos is given by [4]

$$\omega = |\kappa - c\mathbf{B}| + b, \quad (2.1)$$

where  $c$  and  $b$  depend on the distribution function of the background electrons, whose explicit forms will be discussed shortly. For small fields, this can be written as

$$\omega = K - c \frac{\kappa \cdot \mathbf{B}}{K} + b, \quad (2.2)$$

where  $K = |\kappa|$ . If the free neutrinos have some mass  $m \ll K$ , this relation should be modified to

$$\omega = K + \frac{m^2}{2K} - c \frac{\kappa \cdot \mathbf{B}}{K} + b, \quad (2.3)$$

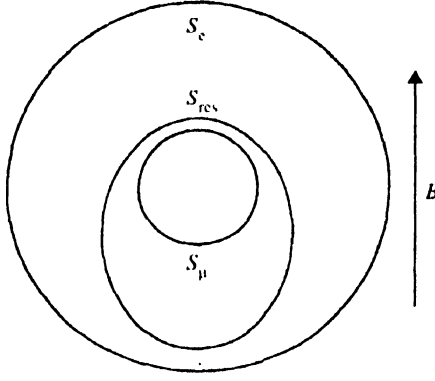
neglecting higher order terms in the mass.

The extra  $\mathbf{B}$ -dependent term can affect resonant neutrino conversion in the stellar core

[6]. To see this, we start from the Hamiltonian governing neutrino propagation in the vacuum, assuming a two-level system :

$$H = \begin{pmatrix} -\frac{\Delta m^2}{4K} \cos 2\theta & \frac{\Delta m^2}{4K} \sin 2\theta \\ \frac{\Delta m^2}{4K} \sin 2\theta & \frac{\Delta m^2}{4K} \cos 2\theta \end{pmatrix}, \quad (2.4)$$

where  $\Delta m^2 = m_2^2 - m_1^2$ , the mass squared difference of the two eigenstates, and  $\theta$  is the mixing angle. We have omitted a term proportional to the unit matrix, since that is irrelevant for our discussion.



**Figure 1.** The relative positions of the neutrino-spheres and the surface of resonance

In presence of the extra terms due to matter and magnetic field, the Hamiltonian is modified :

$$H = \begin{pmatrix} -\frac{\Delta m^2}{4K} \cos 2\theta - c & \frac{\kappa \cdot B}{K} + b \\ \frac{\Delta m^2}{4K} \sin 2\theta & \frac{\Delta m^2}{4K} \cos 2\theta \end{pmatrix} \quad (2.5)$$

Here, once again the contribution to  $b$  and  $c$  from neutral current has been omitted, since it is identical for both neutrinos. The contributions from the charged current interactions affect only the  $\nu_e$  state. To the leading order in the Fermi constant, these are given by [4, 7]

$$b_e = \sqrt{2} G_F (n_e - n_{\bar{e}}),$$

$$c_e = -2\sqrt{2} e G_F \int \frac{d^3 p}{(2\pi)^3} \frac{1}{2E} \frac{d}{dE} (f_e - f_{\bar{e}}), \quad (2.6)$$

where  $f_e$  and  $f_{\bar{e}}$  are the Fermi distribution functions for the electron and the positron, and  $e$  is the charge of the positron. For a degenerate electron gas at zero temperature, we can put  $n_e = 0$ , and evaluation of the integral in  $c_e$  yields

$$c_e = \frac{e G_F}{\sqrt{2}} \left( \frac{3n_e}{\pi^4} \right)^{1/3} \quad (2.7)$$

The condition for resonance [6] is obtained by equating the two diagonal elements of the modified Hamiltonian  $\tilde{H}$ , which reads

$$\begin{aligned} \frac{\Delta m^2}{2K} \cos 2\theta &= b_e - c_e \frac{\boldsymbol{\kappa} \cdot \mathbf{B}}{K} \\ &= \sqrt{2} G_I n_e - \frac{e G_F}{\sqrt{2}} \left( \frac{3n_e}{\pi^4} \right)^{1/3} \frac{\boldsymbol{\kappa} \cdot \mathbf{B}}{K}. \end{aligned} \quad (2.8)$$

Consider now neutrinos of a certain value of momentum. The left side of this equation is fixed now, since  $\Delta m^2$  and  $\theta$  are fundamental parameters which are not in our hands. On the right side, the value of  $n_e$  for which this equality will be satisfied will now depend on the direction with respect to the magnetic field, because of the quantity  $\boldsymbol{\kappa} \cdot \mathbf{B}$ . In the direction along  $\mathbf{B}$ , the resonance condition can be satisfied for a higher value of  $n_e$  compared to the no-field case, *i.e.*, at a smaller distance from the center. In the opposite direction, since  $\boldsymbol{\kappa} \cdot \mathbf{B} < 0$ , we need a smaller value of  $n_e$ , *i.e.*, resonance will occur farther from the center. Overall, the shape of the surface of resonance will be ellipsoidal. A schematic section of this surface is shown in Figure 1, where this surface of resonance has been called  $S_{res}$ .

To see how it can affect the momentum distribution of the neutrinos coming out, let us first review the situation without any magnetic field. In the proto-neutron star, the neutrinos near the core cannot come out easily, because the density is so large that their mean free path is very small. Once they reach a certain radius where the densities are low enough, their mean free path becomes larger than the radius of the proto-neutron star and they can escape. The surface at this radius is called the neutrino-sphere. Since the cross section of  $\nu_e$  with matter is higher than that of  $\nu_\mu$  owing to charged current interactions, the neutrino-sphere for the  $\nu_e$ 's is at a smaller density, *i.e.*, larger radial distance, than that for the  $\nu_\mu$ . These two neutrino-spheres are schematically shown in Figure 1 with the symbols  $S_e$  and  $S_\mu$ .

Let us now see, after Kusenko and Segrè, how this picture might change in presence of magnetic fields. We have discussed the surface of resonance,  $S_{res}$ . Suppose now this surface lies in between the  $\nu_e$  neutrino-sphere and the  $\nu_\mu$  neutrino-sphere, as has indeed been shown in Figure 1. The  $\nu_\mu$ 's produced in the core would escape before they reach this surface. The  $\nu_e$ 's, however, can convert resonantly to  $\nu_\mu$ 's at the surface of resonance. Since at this point, they are outside the  $\nu_\mu$  neutrino-sphere, they will escape the star once this conversion takes place.

Now comes the crucial point. In directions where the resonance surface is close to the center, the neutrinos come out with larger average momentum, since the temperature there is larger. In opposite directions where the resonance surface is far from the center, the neutrinos have smaller average momentum. This creates the momentum imbalance, and the pulsar gets a kick. Analysis of the situation shows that in order to get a fractional imbalance of the order of 1%, one needs magnetic fields of the order of  $3 \times 10^{14} \text{G}$ , which does not look at all improbable inside a proto neutron star, for which surface fields are of order  $10^{12} - 10^{13} \text{G}$ .

One condition for this picture to work is that, as stated earlier, the surface of resonance has to lie between the two neutrino-spheres. For small values of the mixing angle  $\theta$ , this implies that

$$\Delta m^2 \sim 10^4 \text{ eV}^2. \quad (2.9)$$

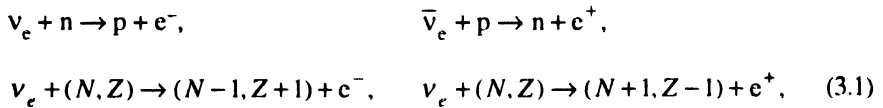
Of course, in the entire discussion, it has to be understood that it does not matter whether the resonant conversion takes the  $\nu_e$  to  $\nu_\mu$  or to  $\nu_\tau$ . But in any case, the value of  $\Delta m^2$  indicated above is in conflict with cosmological bounds on stable neutrino masses, and also is not suggested by any other indication of neutrino oscillation like the solar neutrino problem or the atmospheric neutrino anomaly, but the game is not over. Already, some modifications have been suggested in this picture. One important point, raised by Bisnovatyi-Kogan [8], is that the cross sections for neutrino interactions are modified in presence of a magnetic field. Thus, the neutrino spheres themselves will, in general, be modified, and will in general not remain spherical surfaces. Following this suggestion, Roulet [9] has performed a careful calculation of the cross section of the process  $\nu_e n \rightarrow p e$  in presence of a magnetic field. He concludes that for some ranges of values of the magnetic field and neutrino energy, one actually needs smaller values of  $\Delta m^2$ .

### 3. Supernova shock and neutrinos

A supernova is an explosion. A shock wave is formed in the gravitational collapse of the core of a highly evolved star, which ejects all surrounding material in space, and we see an explosion. The problem is that, in computer simulations of these series of events, the shock was found to be too weak to eject all the surrounding material. The shock wave stalls after it gets out to a distance of a few hundred kilometers. If that happens, all material would fall back and accrete on the dense core already formed, and the result would be a black hole. Nevertheless, supernovas occur, and therefore it is a problem to understand what makes the shock strong enough for that to happen.

We must make a cautionary remark at this point. The simulations, until very recently, were performed with a one-dimensional model of the shock wave. Thus, the results may or may not represent the real situation in three dimensions. Very recently, higher dimensional simulations have been undertaken, and we should wait for their results. But in any case, one can be motivated by the one-dimensional results and try to find out any way of energizing the shock.

Of course, during the gravitational collapse, many neutrinos are emitted. Some time ago, Bethe and Wilson [10] argued that these neutrinos can interact with matter in the form of nucleons or nuclei in the outer mantle through the reactions



The mantle is, of course, outside the neutrino-sphere. Thus, the neutrinos will mostly escape through the mantle. However, a few of them will indeed interact as shown above. This will put extra energy in the nucleons and nuclei, thereby energizing the shock and dissociating nuclei ahead of the shock. However, what they found is that even this is not enough.

After the mechanism of resonant neutrino conversion was proposed to solve the solar neutrino problem, Fuller *et al* [11] examined whether this can help in the problem of supernova shock stalling. The point here is that, the  $\nu_\mu$ 's and  $\nu_\tau$ 's, because of smaller cross section with matter, escape from an inner layer and therefore have larger energy. If they convert to  $\nu_e$  by the resonant conversion mechanism, they will have larger energy than the original  $\nu_e$ 's. Thus, if they interact with the mantle *via* the reaction of eq. 3.1, they will impart more energy to the nucleons. Thus, this mechanism will make the shock revitalization more efficient.

More recently, Akhmedov *et al* [12] have considered another possibility, based on resonant spin-flavor precession which can take place if the neutrinos have some magnetic moment. To keep the discussion simple, they assumed that the neutrinos are Majorana particles, so that no static magnetic moment exists. Only transition magnetic moments can exist in this case. In the case of two generations, there is only one independent magnetic moment, the operator for which connects  $\nu_\mu$  with  $\bar{\nu}_e$ , and equivalently  $\nu_e$  with  $\bar{\nu}_\mu$ .

Bethe and Wilson [10] already showed that the energy absorption co-efficients for the reactions in eq. 3.1 is given by

$$K_i(T_\nu) \approx K_0 Y_i T_\nu^2, \quad (3.2)$$

where  $K_0$  is a constant, the subscript  $i$  stand for either proton or neutron.  $Y_i$  is the relative abundance of  $i$ , and  $T_\nu$  is the neutrino temperature. Thus, the energy absorption co-efficient in the case considered by Bethe and Wilson is

$$\dot{E}_{BW} = K_0 (Y_n T_{\nu_e}^2 + Y_p T_{\nu_\mu}^2), \quad (3.3)$$

assuming the heating is only through the free nucleons. On the other hand, if resonant spin-flavor precession takes place, the  $\bar{\nu}_e$ 's can come from  $\nu_\mu$ 's, as indicated above. So, in that case, one would obtain the energy absorption rate to be

$$\dot{E}_{ALPS} = K_0 (Y_n T_{\nu_e}^2 + Y_p T_{\nu_\mu}^2). \quad (3.4)$$

Because of larger cross section, the  $\bar{\nu}_e$ 's escape from a sphere further from the center of the proto-neutron star at the core compared to the  $\nu_\mu$ 's. Thus, they have a lower temperature, i.e.,  $T_{\nu_e} < T_{\nu_\mu}$ . Hence the resonant spin-flavor mechanism must be more efficient in the reheating. Using the values

$$\begin{aligned} \langle E_{\nu_e} \rangle &\approx 9 \text{ MeV}, \\ \langle E_{\bar{\nu}_e} \rangle &\approx 12 \text{ MeV}, \\ \langle E_{\nu_\mu} \rangle &\approx 20 \text{ MeV}, \end{aligned} \quad (3.5)$$

they obtained

$$\frac{\dot{E}_{ALPS}}{\dot{E}_{BW}} \approx 2.1, \quad (3.6)$$

using  $Y_p \approx 0.47$  and  $Y_n \approx 0.53$ .

A few comments are in order. The mechanism requires that the resonance takes place outside the neutrino-spheres ( $r \sim 50$  km) and inside the position of the stalled shock

( $r \sim 400$  km). For small vacuum mixing angles and for the neutrino energies mentioned above, this requires [12]

$$10 \text{ eV}^2 < \Delta m^2 < 4 \times 10^5 \text{ eV}^2. \quad (3.7)$$

Interestingly, the lower end of this range would not conflict with any cosmological constraints. Moreover, they argue that for such small  $\Delta m^2$ , their mechanism is more efficient than the one without any magnetic moment.

With the range of  $\Delta m^2$  given above, and assuming a magnetic field of the form

$$B_{\perp}(r) = B_0 \left( \frac{r_0}{r} \right)^k, \quad (3.8)$$

where  $r_0$  is the radius of the neutrino-sphere and  $B_0$  is the field at the neutrino-sphere, they can obtain a lower bound for the transition magnetic moment  $\mu$  which ensures that the transition is adiabatic. For  $B_0 = 5 \times 10^{14}$  G and  $k = 2$ , this gives

$$\mu \geq (10^{-14} \text{ to } 10^{-13}) \times \mu_B. \quad (3.9)$$

It is not difficult to construct particle physics models which predict neutrino magnetic moments in this range.

#### 4. Neutrino astronomy

Since the birth of astronomy, we have detected light from distant objects to find out the nature of these objects. In the twentieth century, the detection was extended to other parts of the electromagnetic spectrum, so that now we have x-ray, infra-red and radio astronomy. Within the last quarter of a century, the detection went beyond the electromagnetic spectrum by beginning to detect neutrinos. This endeavour started with the detection of solar neutrinos in the 1970's, and those experiments are still going on. In 1987, neutrinos from a supernova was also detected, and neutrino astronomy has now come of age.

Neutrino astronomy has its advantages and disadvantages over photon astronomy. The main disadvantage is that, since neutrinos have much smaller cross section with the detector as compared with the photons, one needs large detectors. But the advantages are many. Neutrinos suffer hardly from any distraction during their journey. They arrive directly in line from the source. They can bring astrophysical information from cores of various object (like the sun) which photons cannot.

Since my talk excludes solar neutrinos, I will not discuss various operating as well as upcoming solar neutrino detectors. I will discuss another class of detectors which were inspired by the success of the solar neutrino detectors as well as the observation of neutrino pulse from SN1987A. These are detectors for Ultra High-Energy (UHE) neutrinos.

There are two questions about the UHE neutrino telescopes : (1) what kind of new phenomenon will be observable by them ; and (2) what kind of event rates can one expect.

As for the first question [13], one might expect to detect the diffuse neutrino emission from our galaxy. There are also interesting extragalactic sources, and we list a few :

Active galactic nuclei (AGNs) ; These are regions of new star formation at the center of galaxies. Protons and electrons are accelerated to high energy by

shock waves. The charged particles remain trapped by the diffuse magnetic field. But there are reactions of the type  $p + \gamma \rightarrow n + \pi^+$ , and neutrons escape to form cosmic rays. Neutrinos are created from charged pion decays, and their energies will be comparable to those of the cosmic rays.

- Gamma ray bursters (GRBs) : These are sources of huge gamma ray bursts, which are suspected to occur due to merger of neutron stars.
- Topological defects (TDs) : If there are topological defects like cosmic strings, we expect neutrino fluxes from them.

**Table 1.** Upward  $\mu^+ + \mu^-$  event rates per year for all nadir angles for a detector with effective area  $0.1 \text{ km}^2$ , with two different values of the threshold energy From Ref [18]

Flux	Ref	Threshold $\mu$ -energy	
		1 TeV	10 TeV
AGN	[19]	31 – 33	6 – 7
AGN ( $p\gamma$ )	[20]	54 – 56	29 – 37
AGN ( $p\gamma$ & $pp$ )	[20]	2130 – 2258	433 – 479
GRB	[21]	12 – 13	5 – 6
T D	[22]	0.007	–

There may also be other unexpected sources. But let us now turn our attention to the second question.

The answer to the second question depends on the interaction of neutrinos with nucleons and electrons which constitute detector material. Calculation of the cross section with nucleons require knowledge of nucleon structure functions. The structure functions are functions of two variables. One of them is usually taken to be  $Q^2 = -q^2$ , where  $q^\mu$  is the 4-momentum exchanged between the neutrino and the nucleon. The other is the Bjorken variables,  $x$ , which, in the rest frame of the interacting nucleon, is given by

$$x = \frac{Q^2}{2m_N E}, \quad (4.1)$$

$E$  being the energy carried off by the intermediate vector boson. For UHE neutrinos,  $E \approx E_\nu$ , the energy of the incoming neutrinos. Thus, we want structure functions at very small  $x$ . For example, if one wants to consider  $E_\nu \sim 10^9 \text{ GeV}$ , one needs structure functions at  $x \sim 10^{-6}$ .

So far, no experiment has measured structure functions to such low values of  $x$ . The lowest values of  $x$  have been probed by the  $ep$ -collider HERA, which can go as low as about  $10^{-4}$ , and these HERA results have been available only very recently. In order to find cross sections for smaller values than this, one needs to extrapolate these results.

Gandhi *et al* [14] have performed extensive analysis of the known regime of structure functions and extrapolated them to smaller  $x$ . With these extrapolations, they calculated neutrino-nucleon cross sections, and found that their results are substantially higher than the ones



calculated with earlier extrapolations of structure functions [15]. The reason for the difference is twofold. First, they used the structure functions derived by the CTEQ collaboration [16] from the HERA results which were not known earlier. Second, they use a mixture of various extrapolation techniques to make the extrapolation more reliable for small  $x$ . Their results now form the standard framework in which the cross sections of UHE neutrino detectors are calculated. With their results, we now present the event rate expected from various sources mentioned earlier. This appears in Table 1.

In viewing this table, one has to remember the following. The fluxes of neutrinos from various kinds of sources described above is not well-known. There are several calculations of neutrino fluxes from AGNs, for example. We have therefore presented the expected event rates corresponding to these different results. Also, the first calculations for AGNs considered neutrinos created from the  $p\gamma$  reactions. A recent calculation also put in neutrinos created from  $pp$  reactions. This increases the expected fluxes fantastically, as can be seen from Table 1.

Because these numbers are accessible to experiments, a few experiments are planned. These are all under-water or under-ice detectors. The AMANDA detector at the south pole has been completed recently. The others, which are at various stages of developments, are (1) BAIKAL neutrino telescope, at a depth of 1 km in Lake Baikal in Siberia ; (2) NESTOR, at a depth of 3.5 km in the Mediterranean near Pylos, Greece. Another one, DUMAND, at a depth of 4.7 km in the ocean 30 km off the island of Hawaii, has been abandoned midway.

## 5. Neutrinos in cosmology

The importance of neutrinos in cosmology derives from the fact that they are the most dominant particles in the universe, apart from photons. It was believed for a while that they could be the dark matter of the universe, for which various indications exist at various scales. These indications will not be reviewed here.

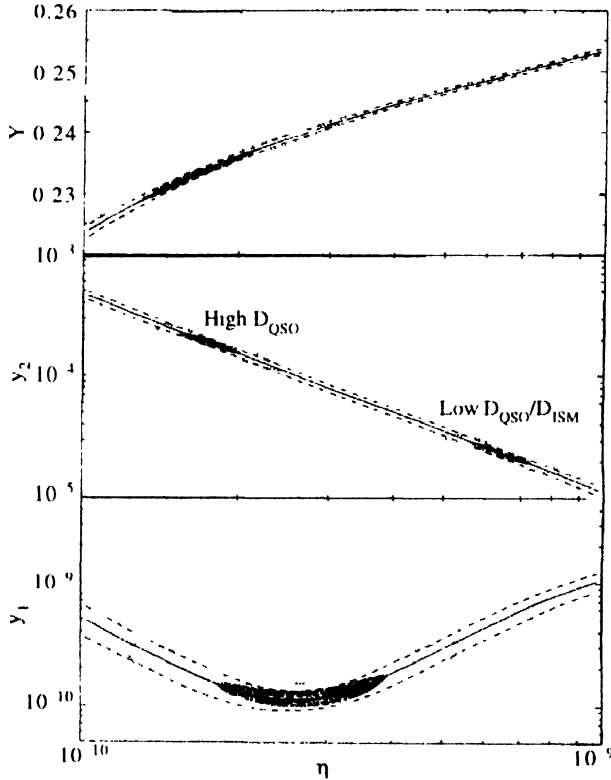
At first, it was believed the neutrinos can constitute all of the dark matter in the universe. Later it was realized that in such a universe filled with light neutrinos, it is difficult to form structures. An alternative, cold dark matter scenario was favored then. But neutrinos staged a comeback with the publication of the COBE data, which showed that not enough structure can be made with CDM at large scales. Now, it is believed that hot dark matter constitutes about 20–30% of the universe, and of course neutrinos are the prime candidates for hot dark matter. This, by now, is part of the folklore, and so I will not get into details. I will rather talk about something recent, as promised.

There are some recent measurements [24] of deuterium abundance in the universe which imply a much lower value of the quantity than was believed before. If this value of the deuterium abundance is believed, this implies a larger value of the parameter  $\eta$  which stand for the baryon to photon number in the universe, as seen from Figure 2.

Steigman *et al* [25] have explored the possible implications of this observation. If we take the value of  $\eta$  dictated by this observation, it would imply that the primordial Helium abundance is much larger than what was believed so far. This higher value would be inconsistent with the observations on primordial Helium abundance.

However, the plots in Figure 2 assume three massless neutrino flavors contributed to the energy density of the universe at the time of Helium synthesis. If, instead, we assume the number of flavors to be two, a better agreement is obtained.

Of course, we know that there are three kinds of neutrinos,  $\nu_e$ ,  $\nu_\mu$  and  $\nu_\tau$ . The direct measurements of the masses of these particles indicate that the  $\nu_e$  mass must be smaller than a few eV, and the  $\nu_\mu$  mass should be smaller than about 250 keV. Since the Helium synthesis occurred when the temperature was about an MeV, both these neutrinos must have been effectively massless at the time. However, the experimental upper limit of  $\nu_\tau$  is 23 MeV. If the mass is really close to that upper limit,  $\nu_\tau$  would not count as an effectively massless species. And then the number of effectively massless neutrino species would be two.



**Figure 2.** The dependence of various abundances on the parameter  $\eta$  are shown with dotted lines. The top panel shows the abundance of Helium, the middle panel of deuterium, and the lower panel of Lithium. The observations are marked on this plot. The new data appears in the lower right end of the middle panel. From Ref. [25]

Thus, if we take this piece of data seriously, one implication is that the  $\nu_\tau$  mass should be larger than an MeV. One can of course argue about how reliable is the data. Or how reliable are the data on primordial Helium and Lithium abundance. I am not qualified to make a comment on this issue.

### Acknowledgments

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- [25] G Steigman, N Hata, S A Bludman and P Langacker *Phys. Rev.* **D55** 540 (1997)